Joint Capabilities and System-of-Systems Solutions: A Case for Crossing Solution Domains

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Abstract

Recognizing the need to succeed in a new multilateral, asymmetric threat environment, the U. S. Department of Defense has initiated a radical transformation in operations to promote agility and enhance responsiveness. The transformation process, as well as the resulting new order of operations, relies heavily on system-of-systems solutions to bridge existing gaps in operations. To date, a pervasive, and possibly detrimental, assumption has dominated the program management arena: management tools and methods that work for single systems apply equally well to the acquisition of system-of-systems solutions. This technical note questions the general assumption that single-system methods are effective in a system-of-systems arena. Taking the position that the field, as a whole, lacks an adequate understanding of the unique challenges that influence system-of-systems initiatives, this report presents a case for the investigation and adaptation of structural and dynamic modeling techniques to the engineering of systems of systems. The report also includes results from a survey of subject matter experts providing evidence that resource expenditures in areas important to a system-of-systems environment are becoming high priorities.

1   Introduction

> "Measure what is measurable, and make measurable what is not so."
>
> Galileo Galilei (1564–1642)

The need for joint capabilities has stimulated interest in integration and interoperability strategies. As such, system-of-systems[1] solutions represent a new, and important, commodity class in the acquisition domain [Krygiel 99]. In terms of the investment resources allocated to them and the operational value of the capabilities they provide, systems of systems have tremendous implications for U.S. Department of Defense (DoD) performance. To date, a pervasive, and possibly detrimental, assumption has dominated the program management arena: management tools and methods that work for single systems apply equally well to the acquisition of system-of-systems solutions. This report questions the general assumption that single-system methods are effective in a system-of-systems arena. Taking the position that the field, as a whole, lacks adequate understanding of the unique cost drivers that influence system-of-systems initiatives, this report advocates the need for, and potential of, the application of nontraditional decision-support tools in engineering system-of-systems solutions.

We begin the report with an overview of the genesis of joint capabilities (Section 2). We then, in Section 3, relate the findings of a survey of subject matter experts [Brown 05a] and discuss the implications of conflicts between the desire to apply traditional methods and evidence that these methods are not sufficient to address the complexity of system-of-systems efforts. In Section 4, we characterize the likely implications that joint capabilities will have on the acquisition of system-of-systems solutions. In Section 5, we offer a research agenda that calls for the application of tools that have shown value in analogous (non-software engineering) complex domains.

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[1]   For the purposes of this research, a system of systems does not represent a particular implementation method; rather, in this report, a system of systems relates to a broad class of integration and interoperability strategies. See http://www.sei.cmu.edu/publications /documents/06.reports/06tr003.html and http://www.infoed.com/Open/PAPERS/systems.htm for discussions of systems of systems.

2   The Genesis of Joint Capabilities[2]

During the Cold War era, military strategy was predicated on the belief that deterrence was best achieved through arms superiority. The arms race was won by a heavy reliance on scientific-management principles as an organizing paradigm [Hughes 98]. Economies of scale were achieved in arms production through a capital-intensive industrial base that stressed the principles of scientific management: hierarchy, division of work, functional specialization, and the separation of planning from operations. These strategies gave rise to a plethora of individual subcultures with distinct missions, goals, and vocabularies.

From a resource perspective, programs were defined by each armed service unit, collectively submitted to the Office of the Secretary of Defense (OSD) for review and approval, and then incorporated into the President's budget [DoD 03a]. Guidance issued by the OSD at the beginning of the fiscal cycle gave each of the armed services a target that reflected an equitable distribution of resources. Generally, equities were preserved, and programs would get their start without a great deal of scrutiny by the Joint Command.

Traditional system development was command-centric and based on assumptions of known nation-state threats that could be symmetrically balanced with well-defined (and often overwhelming) force capabilities. Systems could be rigorously specified, developed, tested, and placed into operation with clear separation of labor and repeatable, parameterized metrics for cost, schedule, and performance. When these systems went awry, management and independent cost estimators were well equipped to detect and provide insight into problems in a timely manner.

From a transparency and accountability perspective, the scientific-management method of organizing activities simplified the budgeting process and facilitated oversight. But it did so at the expense of the integration and agility needed to deter immediate threats. In the current, post-Cold War context—where complexity and variability dominate—the scientific-management method becomes less useful. In this environment, scaling up from a single system to a system of systems often results in nonlinear diseconomies of scale.[3]

DoD transformation became a compelling objective in the aftermath of September 11, 2001. Military performance goals now stress adaptive planning, accelerated acquisition cycles built on spiral development, output-based management, and a reformed analytic support agenda

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[2]   This section is modified from the article *Joint Capabilities of System-of-Systems Solution*s [Brown 05b].

[3]   *Diseconomies of scale* is an economic concept referring to a situation in which economies of scale no longer function for an organization. Rather than experiencing continued decreasing costs per increase in output, organizations see an increase in marginal cost when output is increased (http://www.investopedia.com).

[DoD 03b]. To maintain an operational advantage, the DoD has shifted focus from mass and firepower to agility and precision [JV20 06]. Quite suddenly, agile, tightly integrated joint operations are needed, in which functional specialists are brought together to provide a specific capability suited to a particular operational context. These joint operations cause a shift from command-centric requirements to edge-enabled [Alberts 03],[4] asymmetric, user-demand-driven requirements.[5] Consequently, the broad-scale use of scientific management as an organizing principle has become suspect [JV10 06].

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[4]   The idea of edge organizations was introduced by Alberts and Evans in the book *Power to the Edge: Command and Control in the Information Age*, in which we find the following: "Edge organizations move senior personnel into roles that place them at the edge. They often reduce the need for middle management whose role is to manage constraints and control measures. Command and control becomes unbundled. Commanders become responsible for creating initial conditions that make success more likely . . ." [Alberts 03].

[5]   This information is paraphrased from an interview with B. Cohen, a Carnegie Mellon Software Engineering Institute Visiting Scientist, at the City University, London in 2005.

3 Evidence that Traditional Methods Are Not Keeping Pace

We have observed problems that DoD organizations have experienced when they rely on traditional methods and tools for system-of-systems acquisition. Witness the Army's ABCS (Army Battle Command System) 6.4 upgrade, of which it was reported that "Significant issues arose in the [system-of-systems] SOS engineering as each program postured for optimum solutions for its program" [Greene 05]. Without adaptations to account for the dynamic and emergent properties of complex systems of systems (in this case, the ability to suboptimize locally for the benefit of the whole), the desired migration to network-centric operations is at risk.

A Q survey[6] of 27 Defense Information Systems Agency (DISA) senior executives investigated the extent to which they established a shared understanding on where to invest scarce resources for information system initiatives [Brown 05a]. A speculative interpretation of Brown's results suggests that traditional software engineering and the changing demands of the new network-centric environment are in conflict.

Table 1 is reproduced from the work by Brown and colleagues [Brown 05a] and is modified to add a column totaling the top three priorities that DISA executives expressed when asked to rank order[7] investment recommendations. Significant for our purposes are the close cumulative scores received by the top four recommendations:

1. conceptualizing stable requirements (53%)
2. modeling tools to elaborate problem-solution domains (49%)
3. building and maintaining shared understanding through life cycles (42%)
4. software applications (41%)

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[6] A *Q survey* provides a means for uncovering stakeholder perceptions of incorrectly specified requirements, looming risks, and hidden costs [Brown 04].

[7] Survey respondents were asked to select up to two highest priority investment recommendations, up to three second highest, up to four third highest, and so on.

Table 1:   Frequency Rates of Investment Priorities

Investment Recommendation	First Priority (%)	Second Priority (%)	Third Priority (%)	Cumulative (%)
Conceptualizing stable requirements	30	11	11	53
Modeling tools to elaborate problem-solution domains	19	26	4	49
Building and maintaining shared understanding through life cycles	4	19	19	42
Software applications	15	11	15	41
Project management/oversight and governance strategies	11	11	4	26
Organizational change management	4	8	12	24
Communication advances	0	4	19	23
Methods for tracing and tracking cascading costs of interdependencies	8	8	4	20
Hardware advances	7	7	0	14

The strong desire to stabilize requirements, as indicated by its top investment ranking, is the bedrock of classic systems engineering. Unfortunately, this desire is at odds with the dynamic, composable, context-dependent nature of system-of-systems requirements. Classic requirements elicitation can lead to requirements that are specified in such detail that concrete solutions can be developed for, at best, some transient state of a system of systems. Alternately, the requirement statements become so vague as to leave the solution space open for interpretation. We believe that systems of systems are better served by a capabilities/requirements expanded trade space[8] (see Section 4.2.2) rather than the symmetric demand structure of classic systems engineering. The expanded trade space is much more aware of user demands and is reactive to asymmetric demands.[9]

The second-ranked call for modeling tools may indicate that DISA executives recognize that the problem space is not structured well enough to allow solutions that can be drawn from current knowledge. This interpretation assumes that models are seen as alternatives to rigid specifications and ways to characterize the feedback loops (see Section 4.3) and dynamic nature of the complex problem-solution space. We therefore interpret this ranking as a tacit acknowledgement of the ill-structured, complex nature of the problem-solution space.

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[8]   *Trade space* is the degree of flexibility in trading performance objectives against each other to achieve best value, as defined by the U.S. Navy's *Acquisition Strategy Decision Guide* (http://www.acquisition.navy.mil/aosfiles/tools/asdg/appendix6.html).

[9]   *Asymmetric demands* are those demands that are not satisfied by the existing supply mechanisms.

According to Bardach, successful resolution of wicked[10] or ill-structured problems often requires complex, cross-cutting solutions (i.e., solutions that require the knowledge and expertise of several professional domains) [Bardach 98]. The frequent use of integrated product teams (IPTs) is an example of this need for multiple professional domains. We speculate that the survey respondents' high desire to build and maintain shared understanding is indicative of the challenges associated with crossing these knowledge boundaries.

The nearly equivalent desire to invest in "software applications" may be evidence of the inertia or comfort with traditional tools (i.e., let technology solve the issues, and let the applications fight it out). Unfortunately, without fresh approaches to these complexity issues, traditional applications that are coded against artificially frozen, stable requirement specifications are doomed to failure.

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[10] The nature of a w*icked* problem is such that attempting to solve it often reveals more complex issues. For more information, see http://en.wikipedia.org/wiki/Wicked_problems.

4 Risks and Implications for Joint Capabilities

Underscoring the ways in which traditional methods are in conflict with the complexities of joint capabilities, the authors' experience with traditional estimation tools has shown that

1. The emerging network-centric, power-to-the-edge [Alberts 03],[11] system-of-systems solution space generates classes of risks that, while evident in traditional systems, do not appear to scale linearly with traditional measures such as lines of code or function points.

2. The heightened risk classes, along with new military performance goals related to network-centric operations,[12] have implications for the acquisition of systems of systems.

4.1 Classes of Risk Heightened in Joint Capabilities

Our research into differentiating cost drivers for complex, software-intensive systems of systems [Anderson 04] has indicated that the following categories of risk are much greater for complex systems of systems than they are for their single-system counterparts:

*   **missing requirements**
    Missing requirements constitute a significant source of estimation error and cost variance related to system-of-systems efforts. Although missing requirements have always troubled significant software systems, the issue escalates with each dimension of system-of-systems complexity: systems, services, knowledge domains, funding sources, users, stakeholders, and interfaces.

*   **organizational and institutional obstacles**
    Joint teams suffer the additional complications of serving many masters. Each stakeholder commonly will have separate external influences—financial, philosophical, if not statutory in nature. These issues generate levels of inter- and intra-team dynamics that are exacerbated by system-of-systems efforts.

*   **life-cycle sustainment**
    Life-cycle sustainment in stand-alone software systems is traditionally low risk.

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[11] Power to the edge is a new approach to command and control proposed by Alberts and Hayes. "*Power to the edge* is about changing the way individuals, organizations, and systems relate to one another and work. Power to the edge involves the empowerment of individuals at the edge of an organization (where the organization interacts with its operating environment to have an impact or effect on that environment) or, in the case of systems, edge devices. Empowerment involves expanding access to information and the elimination of unnecessary constraints" [Alberts 03].

[12] As described in Section 2, the performance goals now stress adaptive planning, accelerated acquisition cycles built on spiral development, output-based management, and a reformed analytic support agenda [DoD 03b].

However, the interdependencies of highly integrated and interoperable systems generate sustainment issues, particularly if constituent parts must be maintained independently. Transferring these systems from development to operations is more difficult in system-of-systems efforts due to the need to maintain system-of-systems interdependencies continuously.

- **team performance**
  Unlike single-system development efforts, system-of-systems programs require exceptional team performance in the face of diverse team composition. Team members often come from disparate organizations with conflicting goals, independent funding, and localized incentives. It takes tremendous leadership, individual commitment, and flexibility to achieve synergistic outcomes in such environments.

4.2 Implications for the Acquisition Process

The implications of heightened system-of-systems risk factors and new military performance goals related to network-centric operations for the acquisition community are unprecedented. Because acquisition transforms goals and decisions into reality, it is the locus where concepts become solidified into real-world tasks and operations. As such, we see at least four implications for the acquisition process.

4.2.1 Breaching of the Classic Division of Labor

The clean, unambiguous division of labor that insulated acquisition efforts in the past will have to be breached. One reason for that change is that rapid deployment needs will not allow the time needed to clarify all ambiguity prior to the acquisition process. In addition, the acquisition arena is not immune from the complexity of joint capabilities; within this arena, we would expect many hurdles to arise over requirements and battles to be fought to prioritize different features [Slate 02].

4.2.2 Complication of the Role of Integrated Architectures

Integrated architectures are expected to provide the blueprint for where and how operations will intersect and overlap to provide joint capabilities [Wolfowitz 02]. This integration will require acquisition activities to integrate operations across organizations—an expanded scope that is synonymous with an expanded trade space. In any system, and especially in a system of systems, quality attributes interact: performance affects modifiability; availability affects safety; security affects performance—and everything affects cost [Bass 99]. There is no principled method for characterizing the interactions among quality attributes, and the value of these attributes will vary with the specific situation [Kazman 00]. System-of-systems efforts, by nature of their expansiveness, will complicate the search for mutually acceptable solutions that meet joint requirements (through integrated architectures). In fact, we expect that the struggle over feature tradeoffs will carry over into the acquisition process. For all

intents and purposes, system-of-systems efforts exacerbate the struggle over competing desires.

4.2.3 Conflicts Arise from Evolutionary Spiral Development

The need for ongoing, rapid, and oftentimes unanticipated deployment requires the use of lean evolutionary and spiral implementation methods [Wolfowitz 02]. However, evolutionary acquisition lacks clarity and thus makes the search for solutions more dynamic and porous than traditional acquisition [Sylvester 03]. Slate stated that the evolutionary and spiral acquisition models make it necessary for acquirers to assume a greater role in the requirements process and for "requirers" (stakeholders in the requirements process) to assume a greater role in the acquisition process. Slate predicts that established organizational relationships will be altered, and such shifts almost always lead to conflict [Slate 02].

4.2.4 Competition Loses Effectiveness

Competition is traditionally seen as an effective means for maintaining a best-of-breed military [DoD 03b]. This competitive dimension will do little to arrest the struggle brought about by joint capabilities requirements. Competitors tend to seek asymmetric competitive advantage, not synergy and compromise. Under adverse conditions, these struggles are likely to express themselves in scope creep, schedule delays, and performance shortfalls.

4.3 Explicit Feedback Loops Are Needed

Even if only some of the above implications actually occur, it appears that the acquisition process will be held captive by the effectiveness of the feedback loops that are established. Feedback loops will be needed to clarify ambiguity in and reduce friction among interdependencies. Management must make these feedback loops explicit. Illuminating, monitoring, and measuring such dynamic behavior is challenging, but necessary to estimate resources and budget properly for system-of-systems acquisition.

The DoD is attempting to leverage the benefits that systems of systems can provide to improve collaboration efforts among the military branches, across government agencies, and with coalition partners. The key words presented in this discussion of joint capabilities (such as spiral, integrated, evolutionary, rapid, agile, trade space, feedback loops, and tradeoffs) indicate complexity, and this complexity places system-of-systems efforts at high risk of setback and failure. Elucidation and illumination of the hidden threats of complexity may provide the ability to reduce the risk associated with these large-scale integration efforts.

4.4 Summary of Risks and Implications

In summary, the risk factors heightened by a system-of-systems environment and the military's new performance goals challenge the acquisition community to

- breach the old labor divisions and form dynamic feedback loops between the acquirer and the requirer as well as among the various autonomous requirer constituents

- become more responsive and agile

- foster supplier competition and innovation that is synergistic

Meanwhile, the system-of-systems engineer must do the following, whether from the acquirer's or requirer's perspective:

- Learn to leverage a dynamic and expanded capabilities/requirements trade space.

- Learn to work in a creative new solution space and not always expect to draw upon known solutions.

- Embrace new boundary artifacts,[13] models, and simulations that promote shared understanding and insight into the complexities of the system of systems.

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[13] A *boundary artifact* is a mechanism to cross knowledge domains. For example, a home's blue print is a boundary artifact that crosses the knowledge domain between the architect and the home owner.

5 Solutions from Analogous Domains

In response to this paradigm shift from classic systems engineering that focuses on system requirements that are stable, known, and able to be specified in detail (well-structured, deterministic systems) to an environment that is driven to produce new dynamic capabilities among autonomous systems often characterized by interactions that evolve over time and with varying situational context (complex, adaptive systems), we must look at system-of-systems development with a different lens. Fortunately, other domains have studied analogous challenges and may provide tools and techniques that can help.

Structural and dynamic modeling tools and techniques have a long history that combines the theory, methods, and philosophy needed to analyze and influence the behavior of complex, adaptive systems [Forrester 91]—in the areas of management [Sterman 00, Weinberg 91], environmental change [Simonovic 03, McGrath 01], strategic planning [Lyneis 99, Stacey 92], and engineering [Karnopp 00, Madachy 96]. These tools are commonly used to analyze complex multidimensional dynamics of open, adaptive systems in order to find nonintuitive points of leverage for improvement or for avoidance of nonintuitive failure modes.

However, these tools are not frequently used to characterize problems and solutions for software-intensive systems. We have, however, observed the use of system dynamic (SD) modeling and simulation techniques that have enabled shared understanding of the dynamic interactions that must take place between people, organizations, and systems in specific aspects of the acquisition of complex systems [Adams 05]. Pfahl and colleagues are doing ground breaking work on the application of SD modeling to software process management [Pfahl 02]. They offer a method for goal-oriented development of SD models called Integrated Measurement, Modeling, and Simulation (IMMoS).

> [IMMoS offers] detailed guidance in the form of a process model …
> enforces precise problem definition, helps to identify stakeholders … defines
> the product flow … provides templates and checklists, and offers hints on
> when and how to reuse information from other software modeling activities
> [Pfahl 02].

Interestingly, this work is motivated not by the complexity of system-of-systems efforts but by the general need to improve software-engineering decision support.

As evidenced by IMMoS, techniques to model dynamic system-of-systems interactions in the organizations that build, sustain, use, and acquire these systems are becoming available. A focused effort is needed to adapt these techniques to software engineering and perhaps to expand the boundaries of software engineering to encompass the organizational and operational challenges that are critical for system-of-systems success.

The Carnegie Mellon® Software Engineering Institute (SEI) has recently committed resources to analyze different approaches to structural and dynamic modeling for their relevance in helping DoD organizations to understand, develop, and acquire systems of systems more effectively. Our goals are to understand the

- variety of approaches that are being used to implement these techniques
- conditions under which different approaches appear to be feasible and successful in meeting objectives that support successful, complex, software-intensive systems acquisition, production, and operation
- problem areas within the software-intensive systems problem space that would be amenable to solutions that involve some version of system dynamics modeling, emergent computation, or anticipatory systems modeling
- adoptability of different approaches for different organizational settings
- value propositions associated with leveraging these tools and techniques

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6 Conclusions

As the DoD makes the revolutionary transformation to network-centric operations, adopting new approaches for understanding and managing the ever-increasing complexity of these systems of systems is critical for success. Common shared understanding of complex contexts, processes, and system attributes is a key capability that is needed to ensure shared commitment among individuals and organizations within armed services units and their coalition partners, as well as among users, developers, and acquirers of the systems of systems that are being generated. The SEI is investigating and attempting to adapt existing tools and techniques from domains that have addressed analogous complex issues into the software engineering tool set. We hope that doing this will let us heed Galileo's advice and make the immeasurable measurable.

If you have experiences related to the adoption or use of the tools for acquisition discussed in this technical note and are willing to be interviewed as part of our study, contact isis-sei@sei.cmu.edu.

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